Crossing the Boundaries to explore baryon resonances

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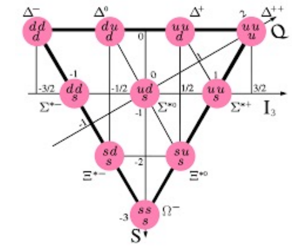
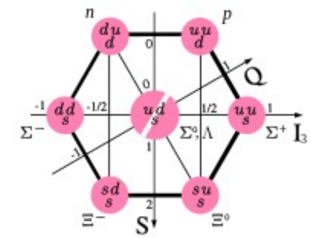
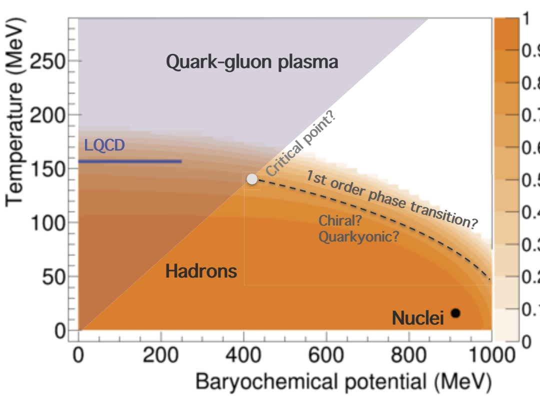
A challenging problem in contemporary physics is the structure of Hadrons

“How are quarks confined into hadrons?”

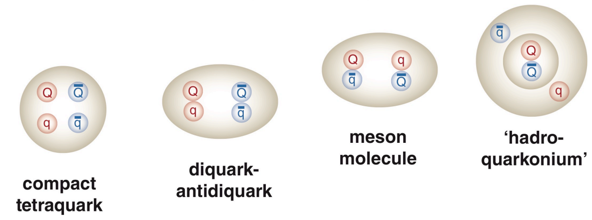


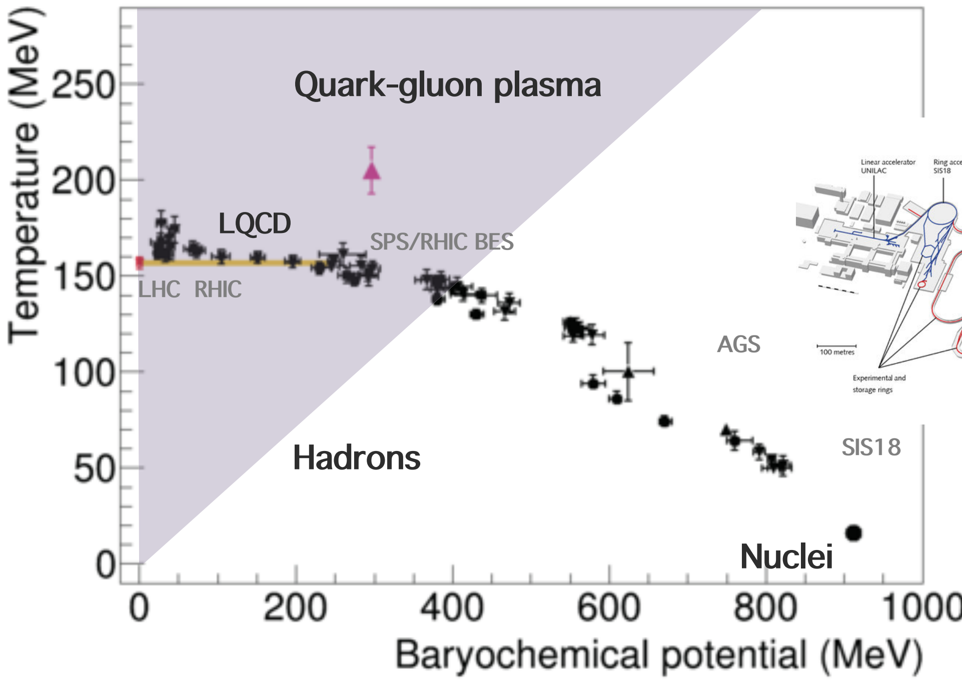


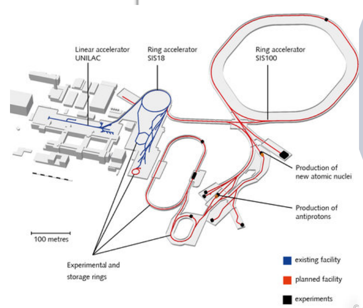
- Hadrons constitute the major part of the visible universe.



- Beyond spectroscopy, today’s experiments have a new level of scope, precision and accuracy on the still unexplored territory of Hadron structures (multiquark and exotic configurations.)







- The nucleon is a key to understand the strong interaction between quarks

(simplest system where the non-abelian nature of the strong interaction is manifest; still has perplexing features)

- Hyperons are also a diagnostic tool

(sufficiently similar to nucleons and being unstable can be more revealing; new territory is to be charted)

- Special role of HADES@SIS

at GSI and PANDA at FAIR

THE
PHYSICAL REVIEW
A journal of experimental and theoretical physics established by E. L. Nichols in 1893
SECOND SERIES, VOL. 76, NO. 12 DECEMBER 15, 1949

Are Mesons Elementary Particles?

E. FERMI AND C. N. YANG*
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received August 24, 1949)

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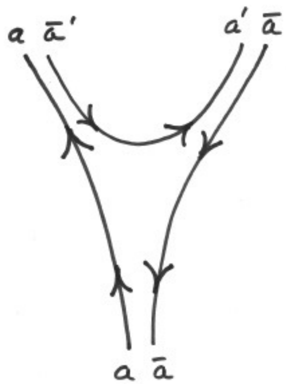
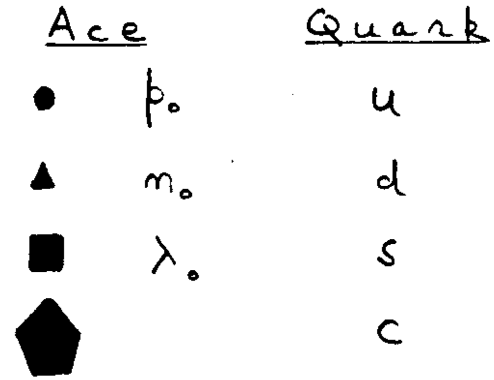
According to this view the positive meson would be the association of a proton and an anti-neutron and the negative meson would be the association of an anti-proton and a neutron. As a model of a neutral meson one could take either a pair of a neutron and an anti-neutron, or of a proton and an anti-proton.

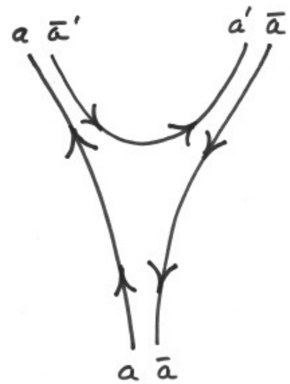


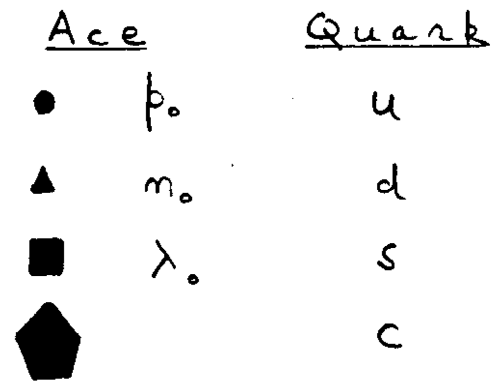


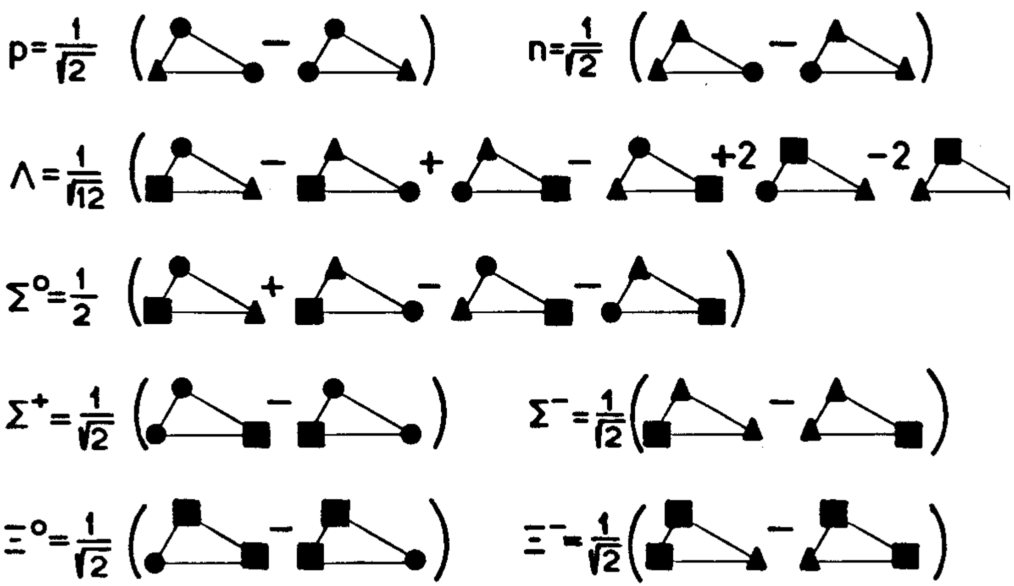
There are 4 aces in a deck of cards, so why call them aces?
(…)
I though that there should be a fourth constituent.

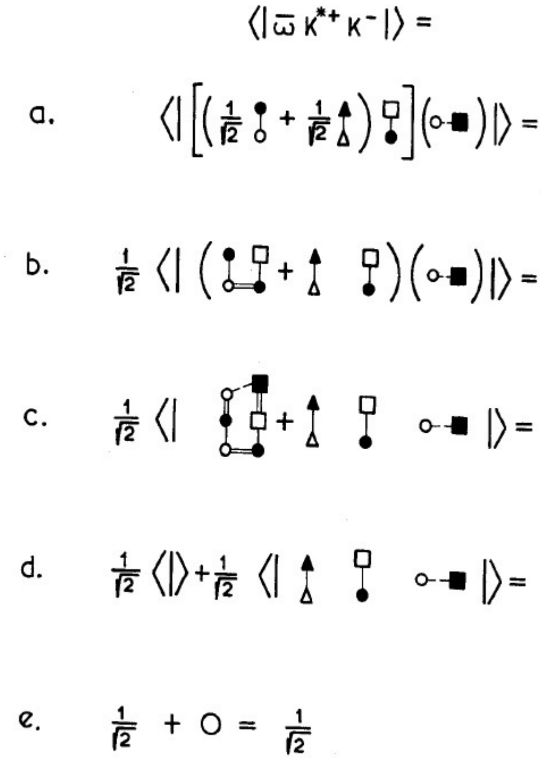
If the τ were known then, I might have called them dice.

Memories of Murray and the Quark Model
George Zweig, Int.J.Mod.Phys.A25:3863-3877,2010





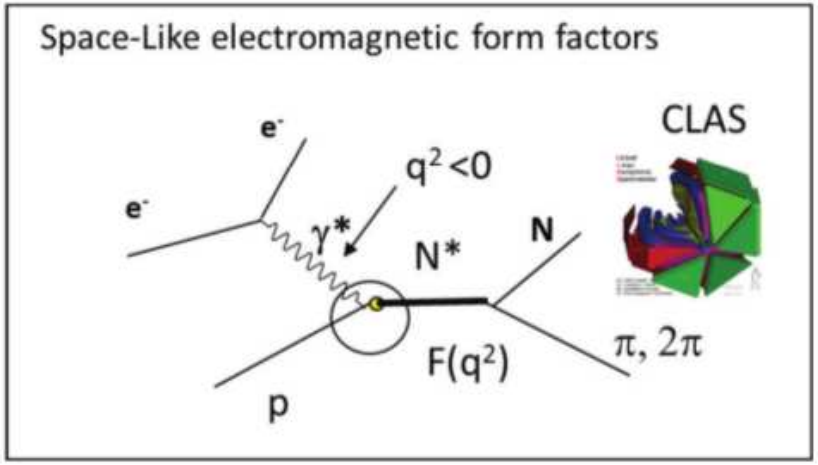


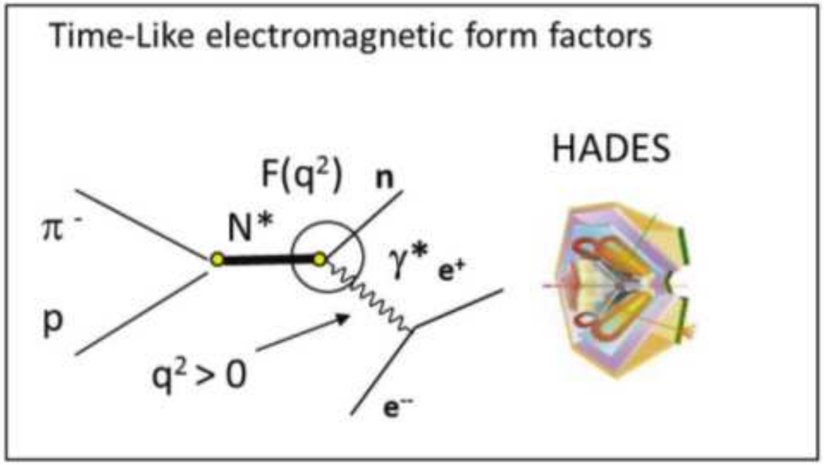


Memories of Murray and the Quark Model
George Zweig, Int.J.Mod.Phys.A25:3863-3877,2010

Two methods of obtaining information on structure of baryons

Figure: B. Ramstein, AIP Conf. Proc. 1735, 080001 (2016) [HADES]





$q^2 \leq 0$: CLAS/Jefferson Lab, MAMI, ELSA, JLab-Hall A, MIT-BATES

$ep \to e'N(\cdots)$; $\gamma^* N \to N^*$

$q^2 > 0$: HADES, ..., PANDA

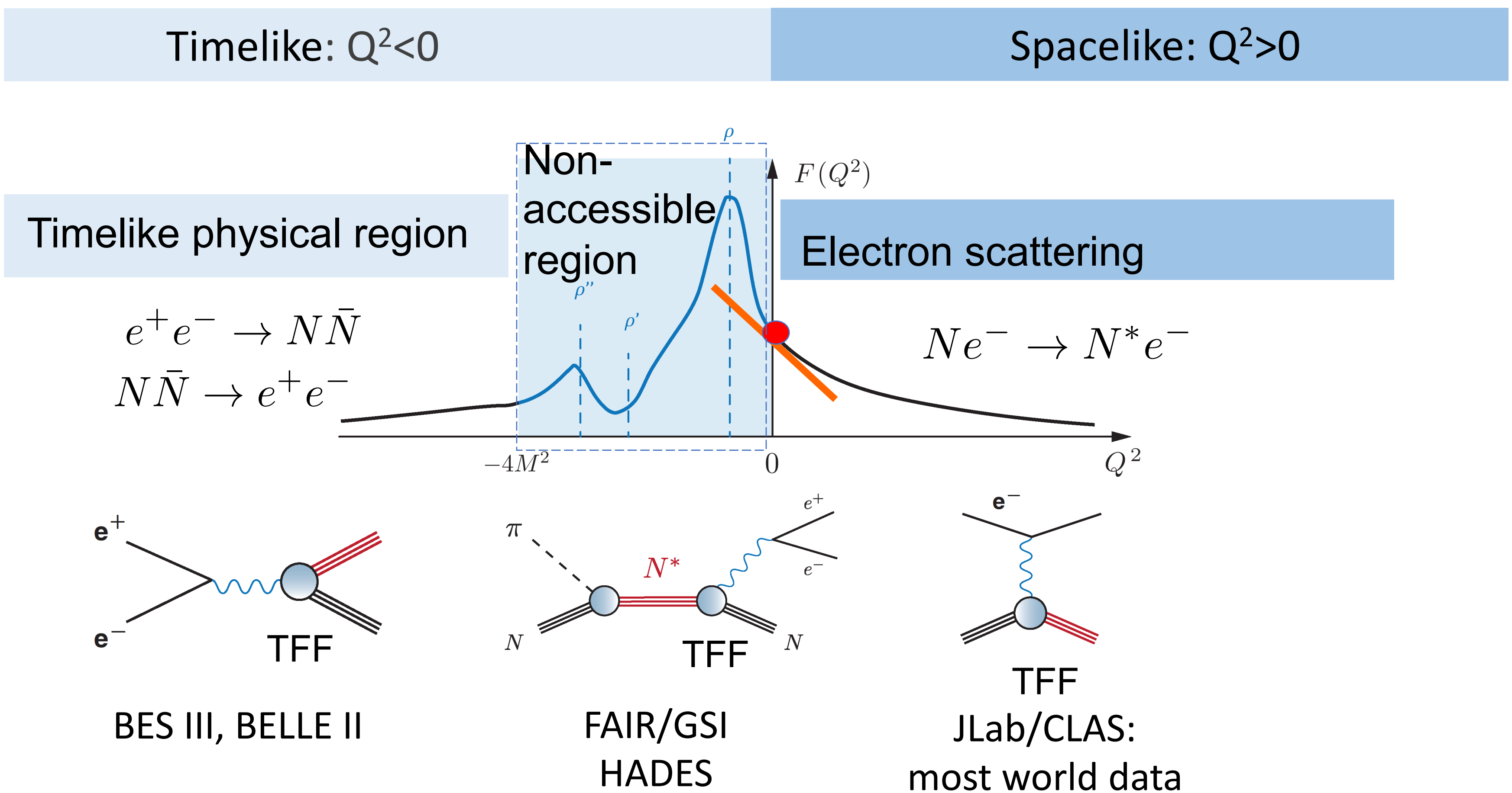
$\pi^- p \to e^+ e^- n$; $N^* \to \gamma^* N \to e^+ e^- N$

Why use of pion beam :

Separation of in-medium propagation and mechanism, because pions are absorbed at the surface of the nucleus whereas in photon and proton absorption occurs throughout the whole nuclear volume.

Crossing the Boundaries to explore baryon resonances

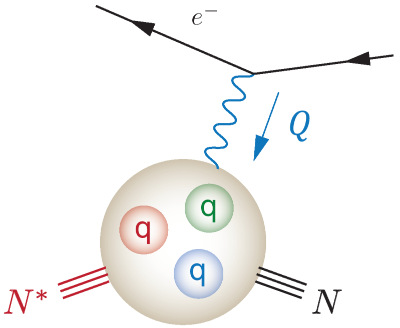
$$Q^2 = -q^2$$



Results have to match at the photon point.

CLAS/JLab electron scattering data constrain interpretation of dilepton production data.

Transition form factors



Baryon resonances
transition form factors

CLAS: Aznauryan et al., Phys. Rev. C 80 (2009)

MAID: Drechsel, Kamalov, Tiator, EPJ A 34 (2009)

See Gernot Eichmann and Gilberto Ramalho
Phys. Rev. D 98, 093007 (2018)

Spacelike form factors:

- Structure information: shape, qqq excitation vs. hybrid, ...

Timelike form factors:

- Particle production channels

Roadmap:
Connect Timelike and SpacelikeTransition Form Factors (TFF)
Obtain Baryon-photon coupling evolution with 4 momentum transfer

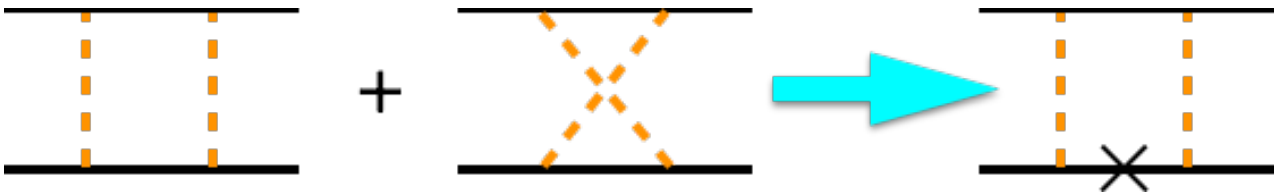
Baryon resonances S=0 PDG

I	S	$J^P = \frac{1}{2}^+$	$\frac{3}{2}^+$	$\frac{5}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{5}{2}^-$
$\frac{1}{2}$	0	$\mathbf{N(940)}$ $\mathbf{N(1440)}$ $N(1710)$ $N(1880)$	$\mathbf{N(1720)}$ $N(1900)$	$\mathbf{N(1680)}$ $N(1860)$	$\mathbf{N(1535)}$ $\mathbf{N(1650)}$ $N(1895)$	$\mathbf{N(1520)}$ $N(1700)$ $N(1875)$	$\mathbf{N(1675)}$
$\frac{3}{2}$	0	$\mathbf{\Delta(1910)}$	$\mathbf{\Delta(1232)}$ $\Delta(1600)$ $\Delta(1920)$	$\mathbf{\Delta(1905)}$	$\mathbf{\Delta(1620)}$ $\Delta(1900)$	$\mathbf{\Delta(1700)}$ $\Delta(1940)$	$\Delta(1930)$

CST© Covariant Spectator Theory

- Formulation in Minkowski space.

- Motivation is partial cancellation



- Manifestly covariant, although only three-dimensional loop integrations.

$$\int_k = \int \frac{d^3\mathbf{k}}{2E_D(2\pi)^3}$$

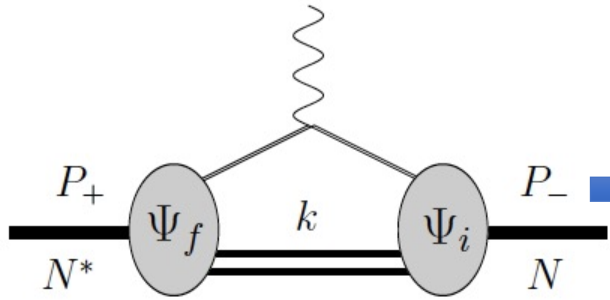
- Provides wave functions from covariant vertex with simple transformation properties under Lorentz boosts, appropriate angular momentum structures and smooth non-relativistic limit.

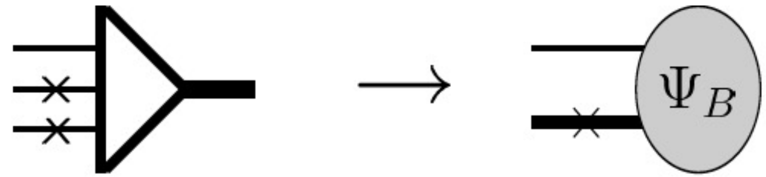
“Murray looked at two pieces of paper, looked at me and said
‘***In our field it is costumary to put theory and experiment on the same piece of pape***r’.
I was mortified but the lesson was valuable”

Memories of Murray and the Quark Model
George Zweig, Int.J.Mod.Phys.A25:3863-3877,2010

Zweig quark is the constituent quark

E.M. matrix element





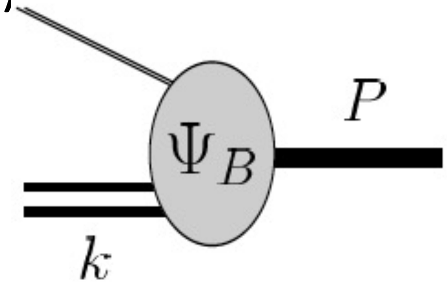
$$\int_{k_1 k_2} \equiv \int \frac{d^4k_1 d^4k_2}{(2\pi)^6}\delta_+(m_1^2 - k_1^2)\delta_+(m_2^2 - k_2^2) = \int \frac{d^3k_1 d^3k_2}{(2\pi)^6 4E_1E_2},$$

$$\int_{sk} = \underbrace{\int \frac{d\Omega_{\hat{\mathbf{r}}}}{4(2\pi)^3} \int_{4m_q^2}^{\infty} ds \sqrt{\frac{s - 4m_q^2}{s}}}_{\int_s} \underbrace{\int \frac{d^3k}{(2\pi)^3 2E_s}}_{\int_k},$$

- **E.M.** matrix element can be written in terms of
an effective baryon composed by an off-mass-shell quark, and an on-mass-shell quark pair (diquark) with an average mass.

- **Baryon wavefunction** reduced to an effective quark-diquark structure.

Nucleon "wavefunction" (S wave)
(symmetry based only; not dynamical based)



- A quark + **scalar**-diquark component
- A quark+ **axial vector**-diquark component

$$\Psi^S_{N\lambda_n}(P,k) = \frac{1}{\sqrt{2}}[\phi^0_I u_N(P,\lambda_n) - \phi^1_I \varepsilon^{\alpha *}_{\lambda P} U_\alpha(P,\lambda_n)] \times \psi^S_N(P,k).$$

Phenomenological function

$$U_\alpha(P,\lambda_n) = \frac{1}{\sqrt{3}}\gamma_5\left(\gamma_\alpha - \frac{P_\alpha}{m_H}\right)u_N(P,\lambda_n),$$

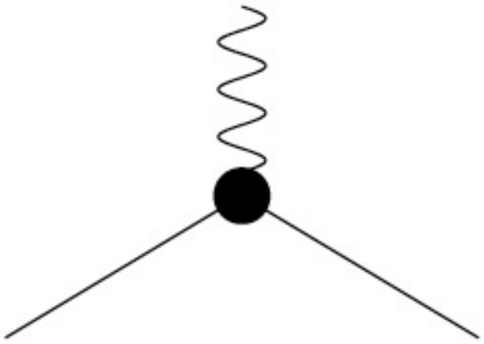
Delta (1232) "wavefunction" (S wave)

- Only quark + **axial vector**-diquark term contributes

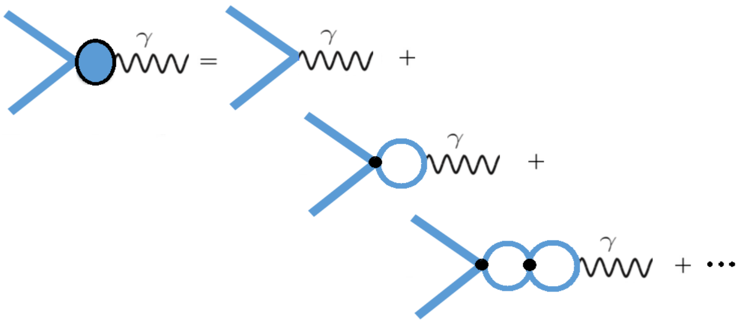
$$\Psi^S_\Delta(P,k) = -\psi^S_\Delta(P,k)\tilde{\phi}^1_I \varepsilon^{\beta *}_{\lambda P} w_\beta(P,\lambda_\Delta)$$

Diquark is not pointlike.

E.M. Current



Quark-photon vertex



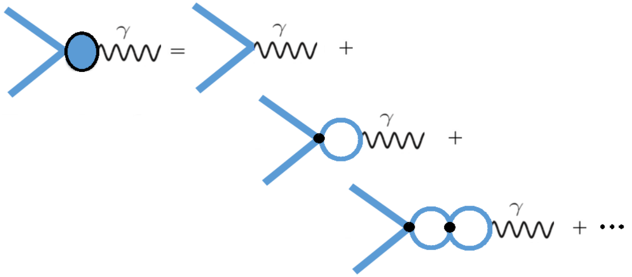
$$\Gamma_\mu(p,Q) = \quad \gamma_\mu \quad + \int \frac{d^4q}{(2\pi)^4} K(p,q,Q) S(q+\eta Q) \Gamma_\mu(q,Q) S(q-\eta Q)$$

Constituent quarks (quark form factors)

$$j_I^\mu = \left[\frac{1}{6} f_{1+} + \frac{1}{2} f_{1-} \tau_3\right] \gamma^\mu + \left[\frac{1}{6} f_{2+} + \frac{1}{2} f_{2-} \tau_3\right] \frac{i\sigma^{\mu\nu} q_\nu}{2M_N}$$

$$f(Q^2) = e + gB(Q^2)e + gB(Q^2)gB(Q^2)e + \cdots = e + \frac{gB(Q^2)e}{1 - gB(Q^2)}$$

if $gB(Q^2) = \frac{\lambda^2}{\Lambda^2 + Q^2}$, then $f(Q^2) = e + \frac{\lambda^2 e}{\Lambda^2 - \lambda^2 + Q^2}$



$$f_{1+} = \lambda + \frac{1-\lambda}{1 + Q_0^2/m_v^2} + \frac{c_\pm Q_0^2/M_h^2}{\left(1 + Q_0^2/M_h^2\right)^2}$$

$$f_{2\pm} = \kappa_\pm \left(\frac{d_\pm}{1 + Q_0^2/m_v^2} + \frac{(1-d_\pm)}{1 + Q_0^2/M_h^2} \right)$$

$$\Gamma_\mu(p,Q) = \gamma_\mu + \int \frac{d^4q}{(2\pi)^4} K(p,q,Q) S(q+\eta Q) \Gamma_\mu(q,Q) S(q-\eta Q)$$

To parametrize the current use Vector Meson Dominance,
a truncation to the rho and omega poles of the full meson spectrum contribution to the quark-photon coupling.

4 parameters

E.M. Current and TFF at the photon point

$$\gamma N \to \Delta$$

$$\Gamma^{\beta\mu}(P,q) = \left[G_1 q^\beta \gamma^\mu + G_2 q^\beta P^\mu + G_3 q^\beta q^\mu - G_4 g^{\beta\mu} \right] \gamma_5$$

- Only 3 G_i are independent:
  E.M. Current has to be conserved

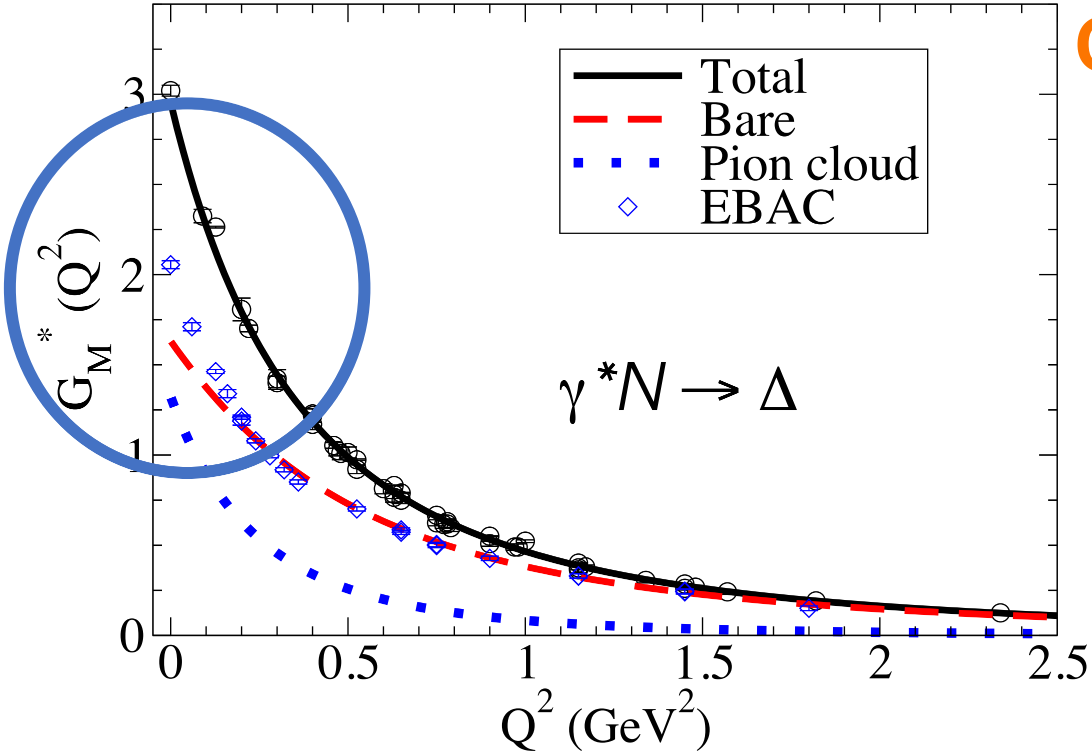
$$q^\mu \Gamma_{\beta\mu} = 0$$ ➡

G_M, G_E, G_C Scadron-Jones popular choice.

Model independent feature

$$\gamma N \to \Delta \qquad G_M^* = G_M^B + G_M^\pi$$

Separation seems to be supported by experiment.
Missing strength of G_M at the origin is an universal feature.



CST© 2009

Bare quark core:

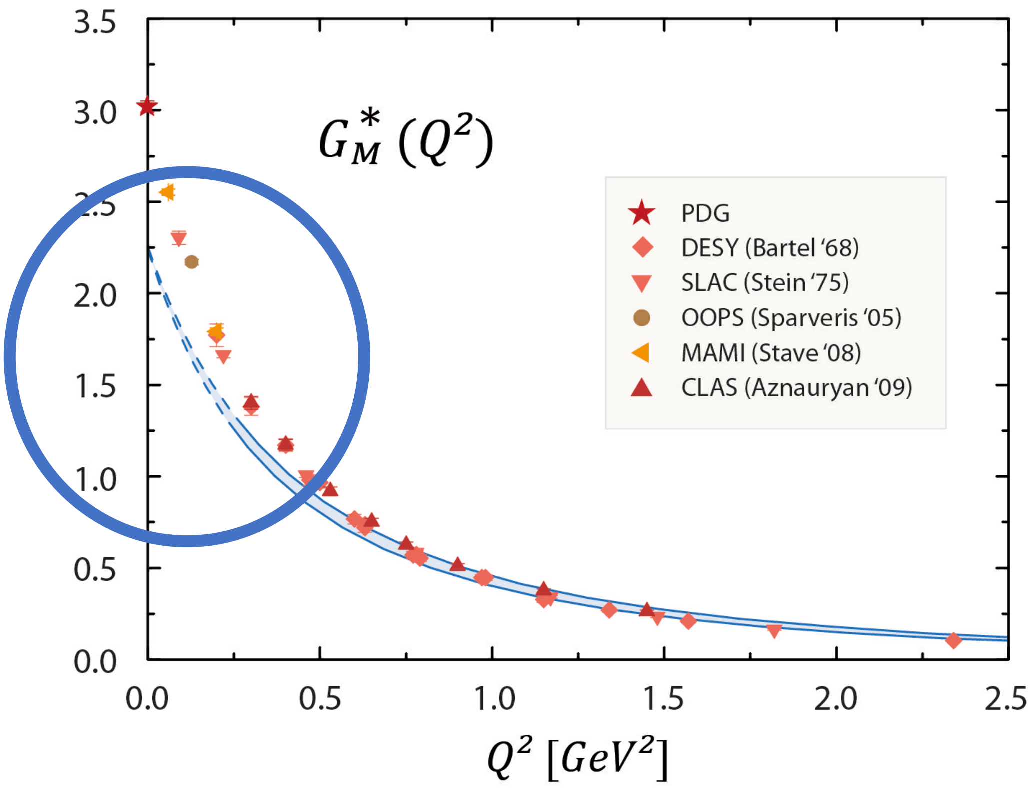
- dominates in the large Q^2 region.
- agrees with other calculations ("EBAC") with pion couplings switched off.

Model independent feature

$$\gamma N \rightarrow \Delta$$

Missing strength of G_M at the origin is an universal feature, even in dynamical quark calculations.

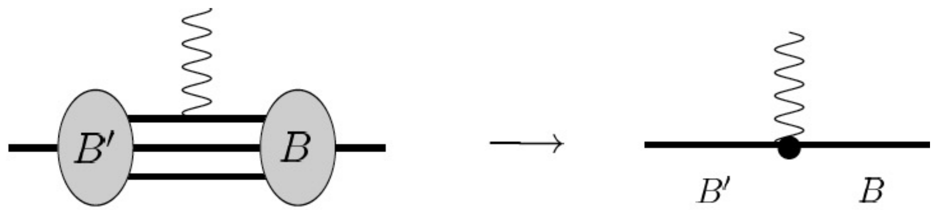
Eichmann et al., Prog. Part. Nucl. Phys. 91 (2016)



Effect of vicinity of the mass of the Delta to the pion-nucleon threshold.

$$G_M^* = G_M^B + G_M^\pi$$

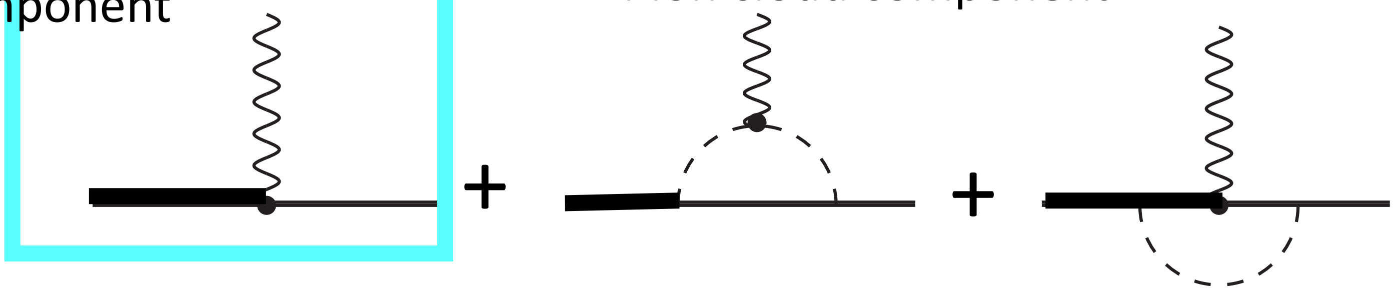
Bare quark and pion cloud components



For low Q^2 : add coupling with pion in flight.

Bare quark component
component

Pion cloud component



$q\bar{q}$ pairs from a single quark included in dressing

Pion created by the overall baryon, not from a single quark

Pion cloud component supressed for high Q^2 $\frac{1}{Q^8}$

VMD as link to LQCD

experimental data well described in the large Q^2 region.

VMD

In the current the **vector meson** mass is taken as a function of the running pion mass.

Pion cloud contribution negligible for **large pion masses**

quark model calibrated to the **lattice data**

Take the limit of the physical pion mass value

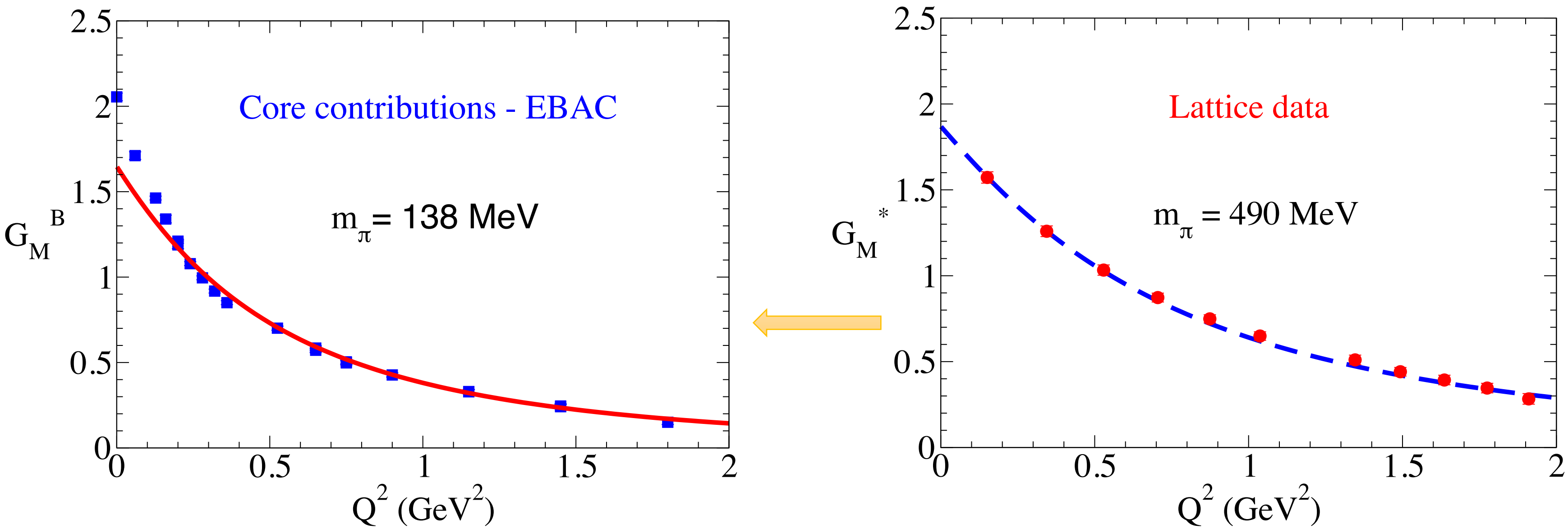
$\gamma N \rightarrow \Delta$

Connection to Lattice QCD

To control model dependence:

CST model and LQCD data are made **compatible.**

G. Ramalho and M. T. Peña, Phys. Rev. D 80, 013008 (2009)

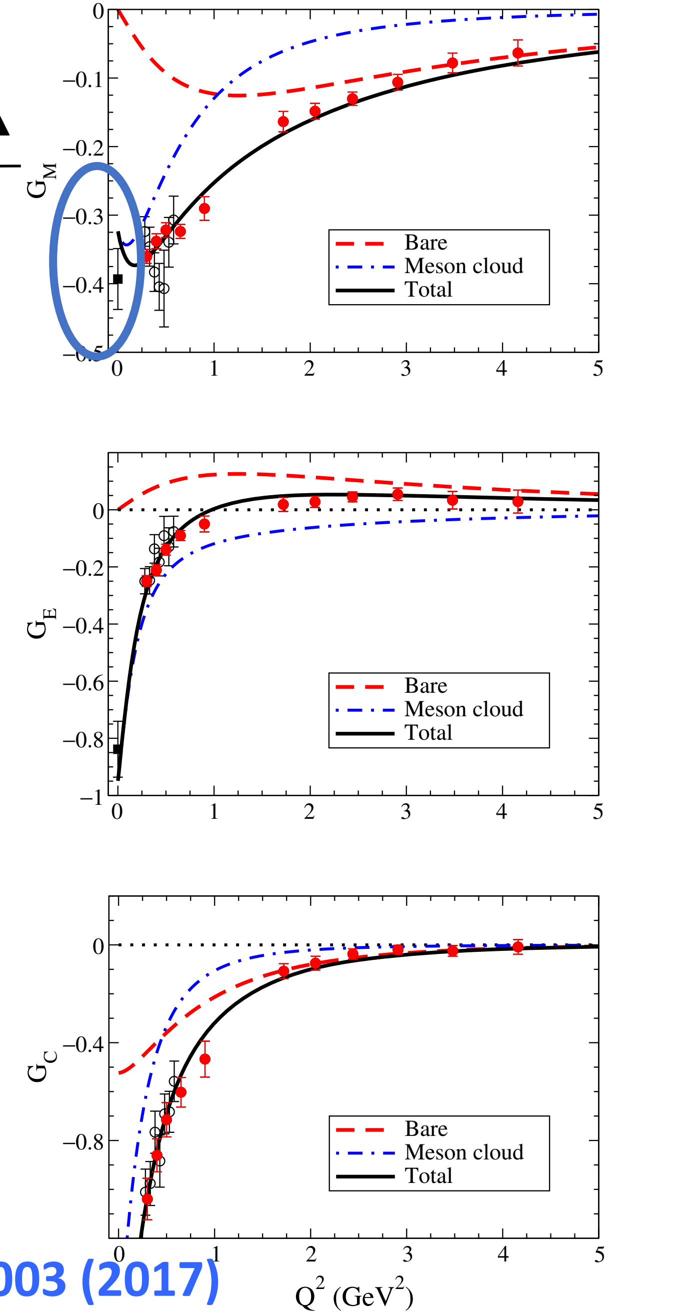


Model (no pion cloud) valid for lattice pion mass regime.

No refit of wave function scale parameters for the physical pion mass limit.

$N \rightarrow N^*(1520)$ **TFFs**

$J^P=3/2^-$ I=1/2
60% decay πN
30% decay to $\pi\Delta$



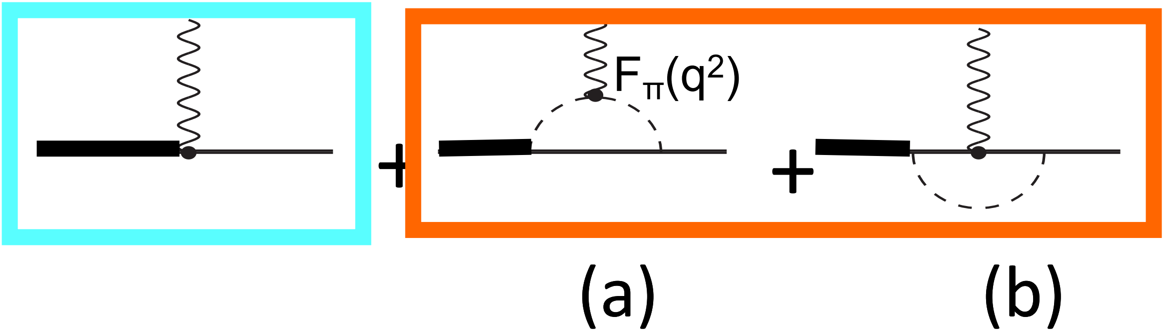
- Bare quark model gives good description in the high momentum transfer region.

- Important role of meson cloud extracted; dominated by the pion due to the π N and $\pi\Delta$ channels branching ratios.

(as in Aznauryan and Burkert, PRC 85 055202 2012)

G. Ramalho, M. T. P. , PHYSICAL REVIEW D 95 014003 (2017)

Extension to Timelike



The residue of the pion from factor $F_\pi(q^2)$ at the timelike ρ pole is proportional to the $\rho \longrightarrow \pi\pi$ decay

Diagram (a) related with pion electromagnetic form factor $F_\pi(q^2)$

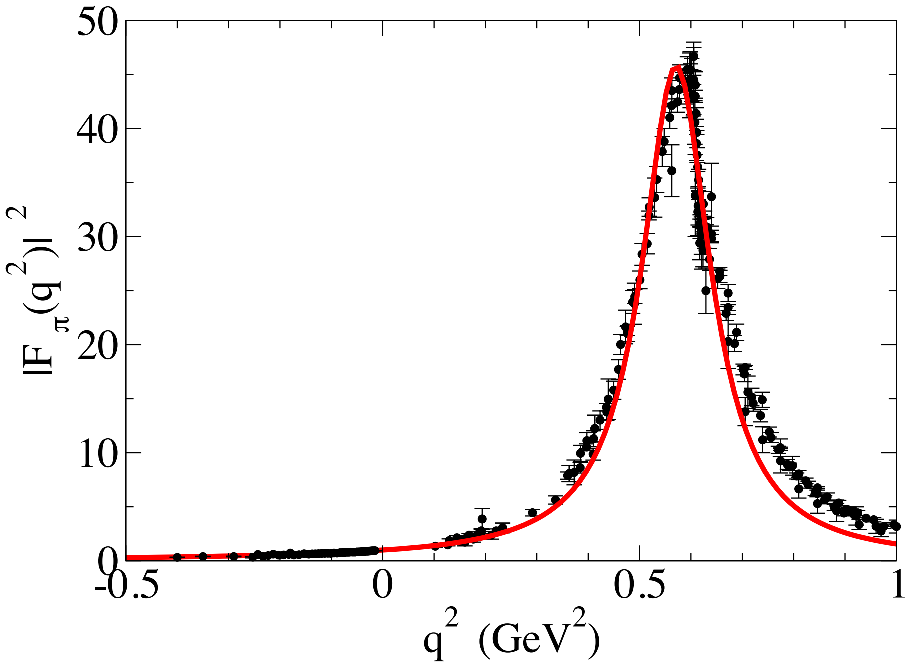
Extension to Timelike

Parametrization of pion Form Factor

$$F_\pi(q^2) = \frac{\alpha}{\alpha - q^2 - \frac{1}{\pi}\beta q^2 \log\frac{q^2}{m_\pi^2} + i\beta q^2}$$

$\alpha = 0.696$ GeV^2

$\beta = 0.178$



Crossing the boundaries

$\Delta(1232)$ Dalitz decay

$$\Gamma_{\gamma^* N}(q;W) = \frac{\alpha}{16}\frac{(W+M)^2}{M^2W^3}\sqrt{y_+y_-}\,y_-|G_T(q^2,W)|^2$$

$$|G_T(q^2;M_\Delta)|^2 = |G_M^*(q^2;W)|^2 + 3|G_E^*(q^2;W)|^2 + \frac{q^2}{2W^2}|G_C^*(q^2;W)|^2$$

$$y_\pm = (W \pm M)^2 - q^2$$

$$\Gamma_{\gamma N}(W) \equiv \Gamma_{\gamma^* N}(0;W)$$

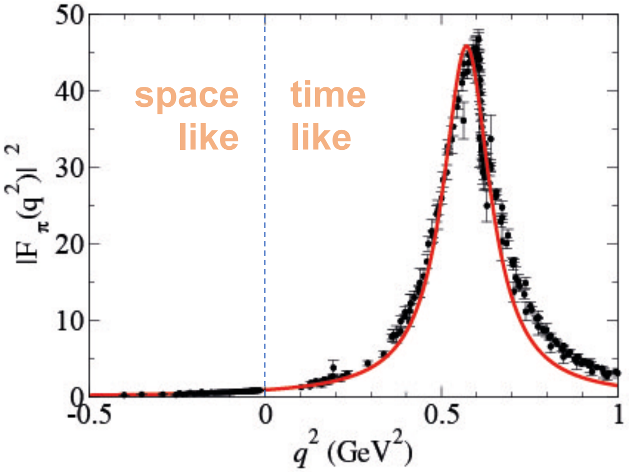
$$\Gamma_{e^+e^-N}(W) = \frac{2\alpha}{3\pi}\int_{2m_e}^{W-M}\Gamma_{\gamma^* N}(q;W)\frac{dq}{q}$$

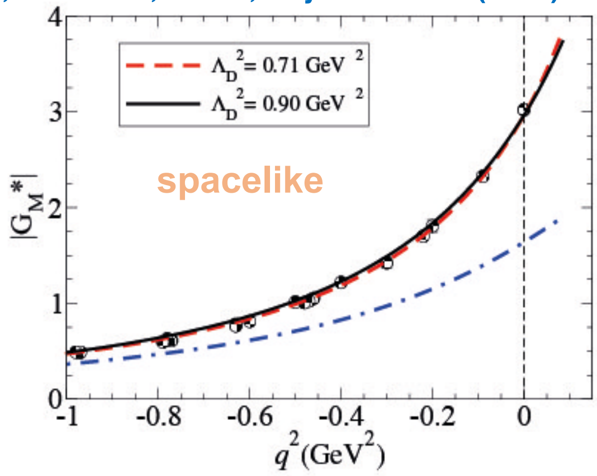
Crossing the boundaries

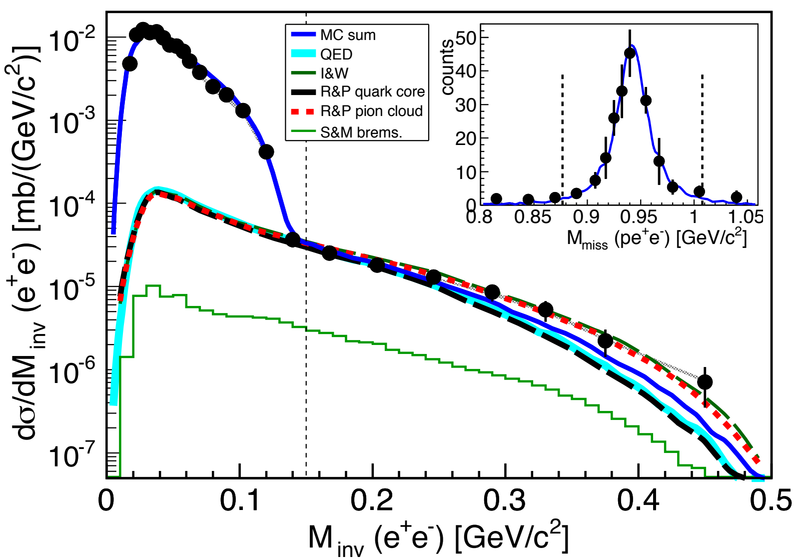
$\Delta(1232)$ Dalitz decay

$\gamma N \rightarrow \Delta$

Ramalho, Pena, Weil, Van Hees, Mosel, Phys.Rev. C93 (2016)







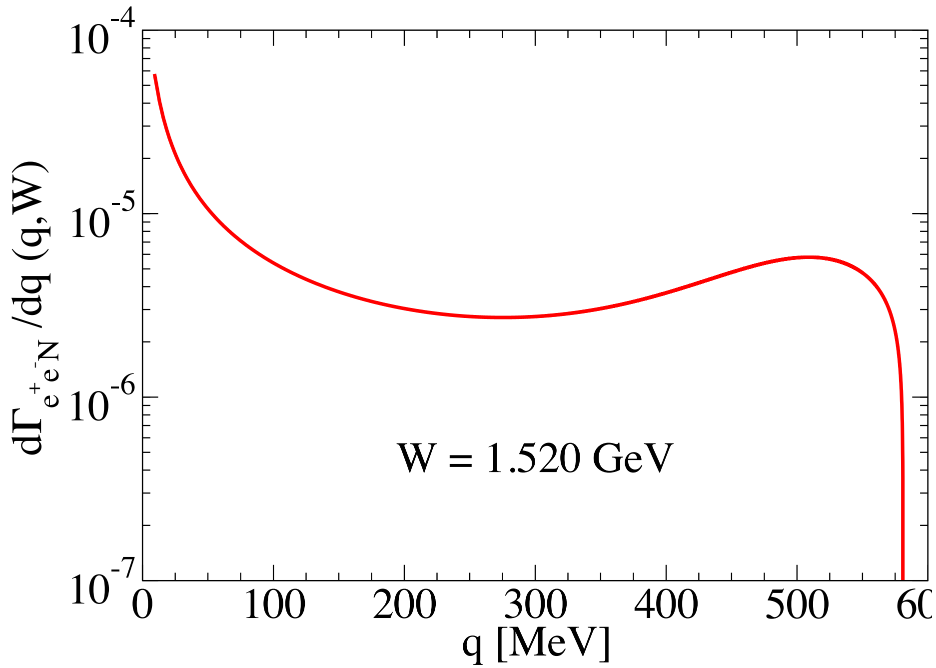
HADES Collaboration,
Phys.Rev. C95 0652205 (2017)

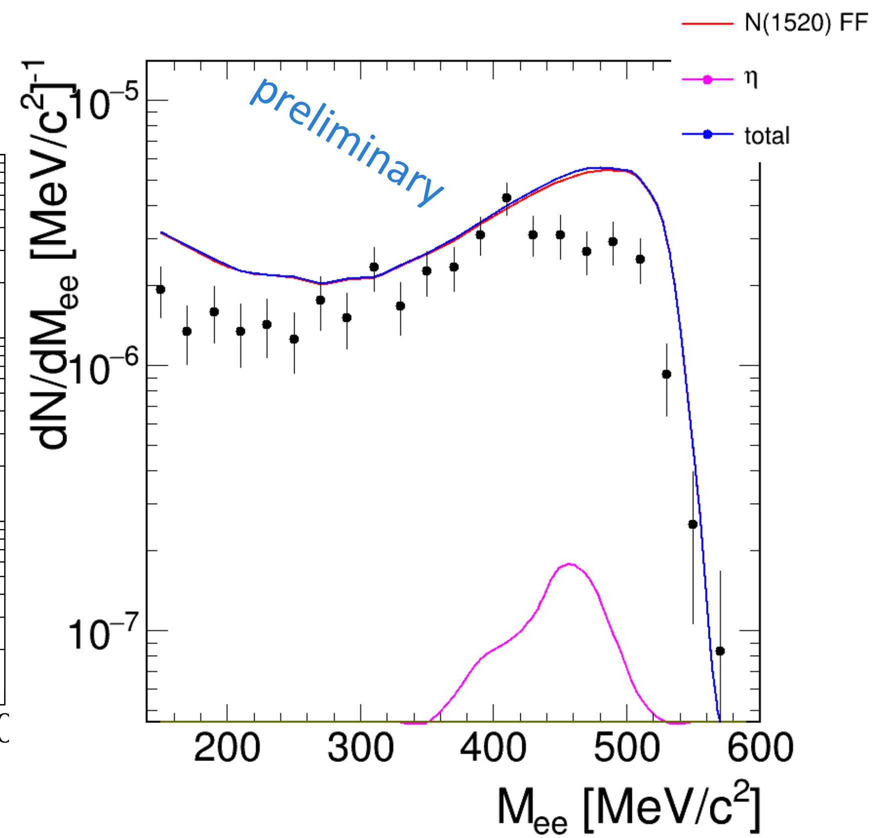
Δ Dalitz decay branching ratio 4.19 x 10^{-5}

Crossing the boundaries

N*(1520) Dalitz decay

True prediction



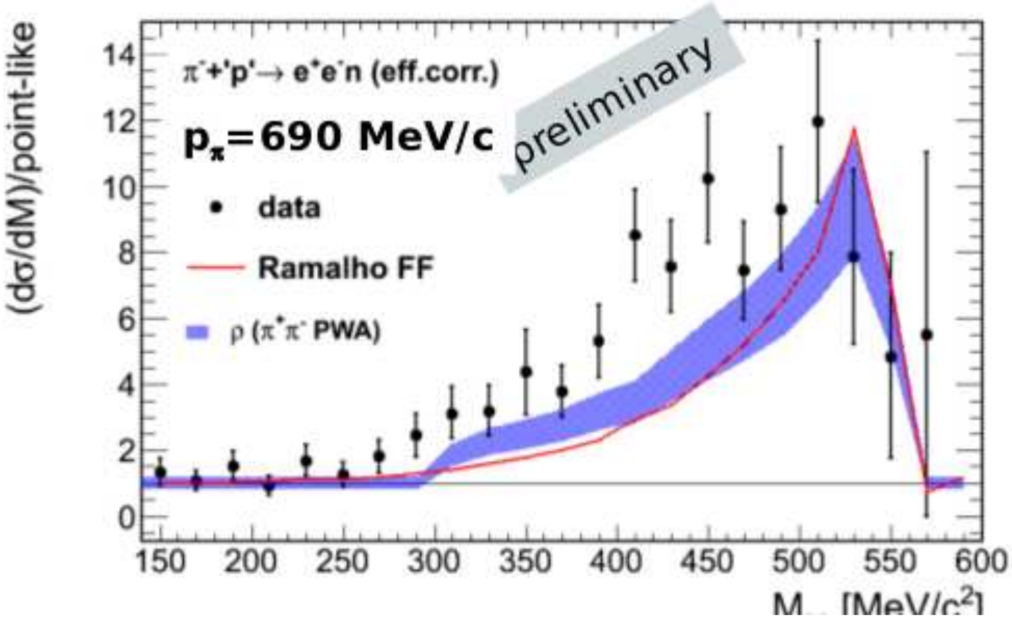


HADES Collaboration
2018

Crossing the boundaries

N*(1520) Dalitz decay

Effect of dependence of e.m. coupling with W   True prediction



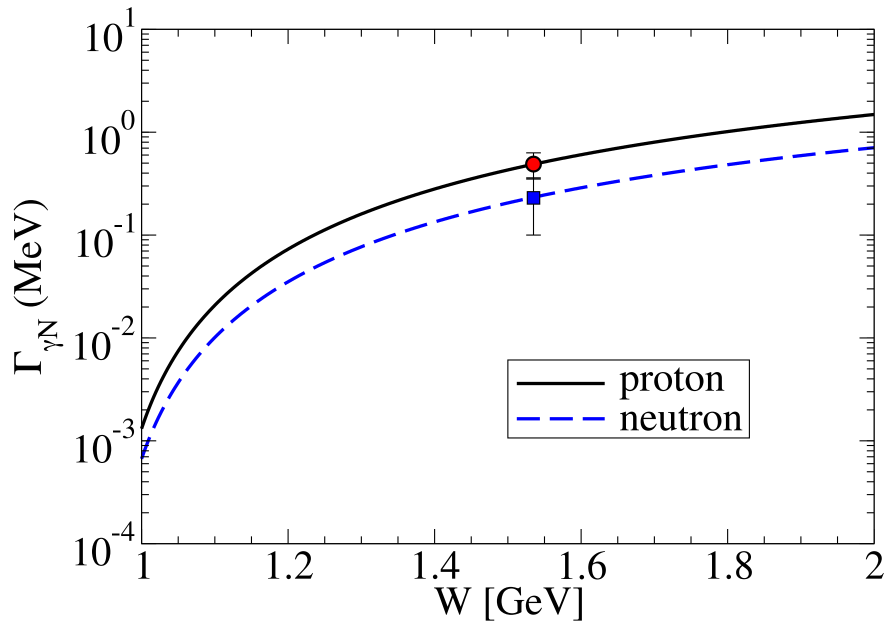
B. Ramstein, NSTAR2019   HADES Collaboration

Ratio to pointlike case

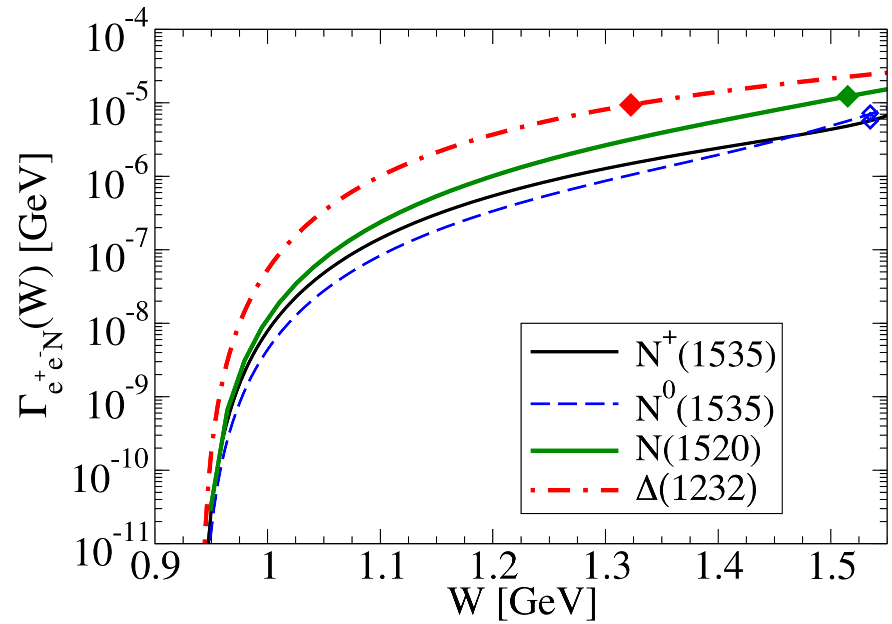
Crossing the boundaries

N*(1535)

$J^P=1/2^-$ I=3/2
~50% decay to π N
~50% decay to η N



Electromagnetic decay



Dalitz decay (compared)

G. Ramalho and M.T. P. Phys.Rev.D 101 (2020) 11, 114008, (2020)

Different results for proton and neutron electromagnetic widths due to iso-scalar term in the meson cloud.

Dalitz decay widths similar for proton and neutron.

	$A_{1/2}(0)$ [GeV$^{-1/2}$]		$\Gamma_{\gamma N}$ [MeV]		
	Data	Model	Estimate	PDG limits	Model
p	0.105 ± 0.015	0.101	0.49 ± 0.14	0.19–0.53	0.503
n	-0.075 ± 0.020	-0.074	0.25 ± 0.13	0.013–0.44	0.240

Extension to Strangeness in the timelike region

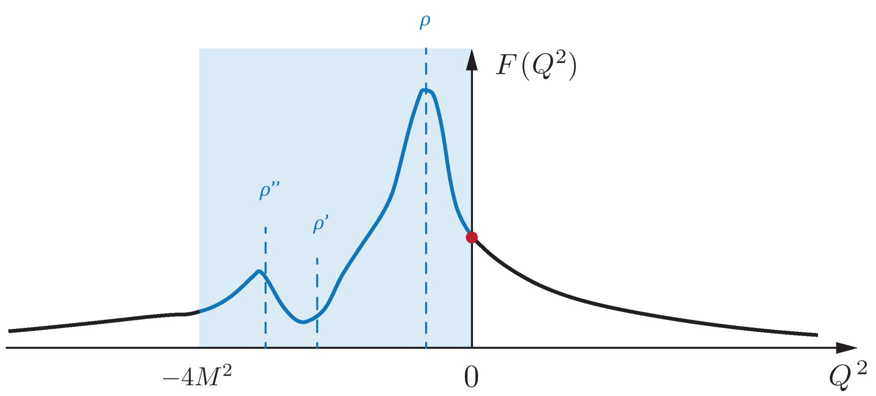
$$e^+e^- \to \gamma^* \to B\bar{B}$$

$$|G(q^2)|^2 = \left(1+\frac{1}{2\tau}\right)^{-1}\left[|G_M(q^2)|^2 + \frac{1}{2\tau}|G_E(q^2)|^2\right.$$
$$= \frac{2\tau|G_M(q^2)|^2 + |G_E(q^2)|^2}{2\tau+1}. \quad \tau = \frac{q^2}{4M_B^2}$$

Effective Form factor that gives the integrated cross section

Unitarity and Analiticity demand that for $q^2 \to \infty$

$$G_M(q^2) \simeq G_M^{\rm SL}(-q^2),$$
$$G_E(q^2) \simeq G_E^{\rm SL}(-q^2).$$



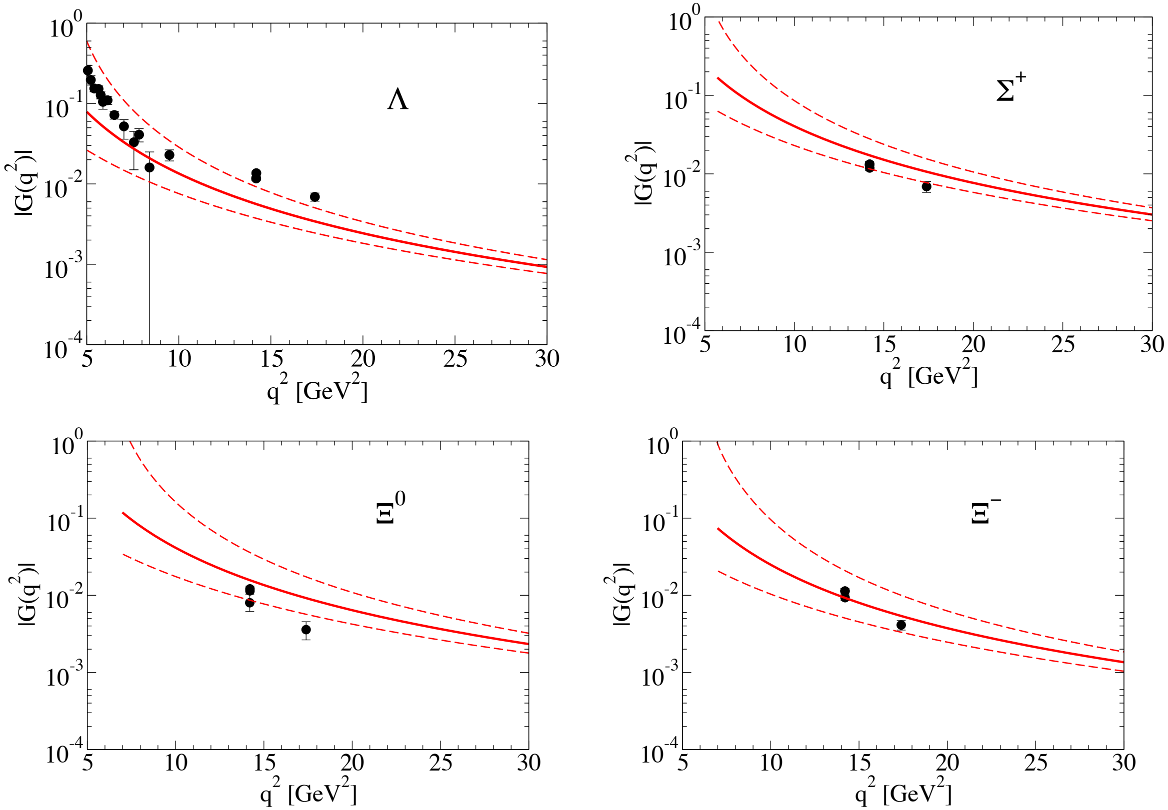
S.Pacetti, R. Baldini Ferroli and E. Tomasi-Gustafsson, Phys. Rept. 550-551,1 (2015)

CST seems to work well at large Q^2.

Extension to Strangeness in the timelike region

$$e^+e^- \to \gamma^* \to B\bar{B}$$

Data from
Babar,CLEO,BESIII



Full line: $G(q^2) = G(2M^2 - q^2)$

Dashed lines: $G(q^2) = G(4M^2 - q^2)$

$G(q^2) = G(-q^2)$

$$G_M(q^2) \simeq G_M^{\rm SL}(-q^2),$$
$$G_E(q^2) \simeq G_E^{\rm SL}(-q^2).$$

G. Ramalho and M.T.P. Phys.Rev.D 101 (2020) 1, 014014, (2020)

Summary

With a CST phenomenological ansatz for the baryon wave functions we described different excited stated of the nucleon, with a variety of spin and orbital motion.

1 Evidence of separation of partonic and hadronic (pion cloud) effects from the Δ (1232)

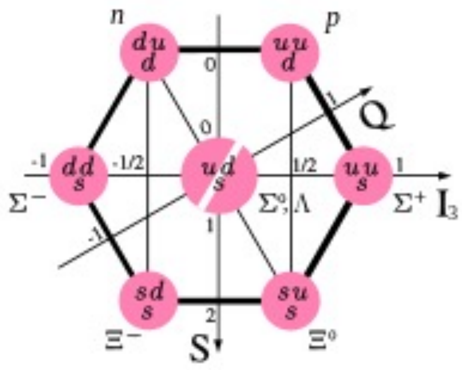
2 Made consistent with LQCD in the large pion mass regime, enabling extraction of "pion cloud" effects indirectly from data.

3 Spacelike e.m. transition FFs for:
N*(1440), N*(1520), N*(1535), …, baryon octet, etc.

4 Extension to timelike e.m. transition FFs and predictions for dilepton mass spectrum and decay widths.

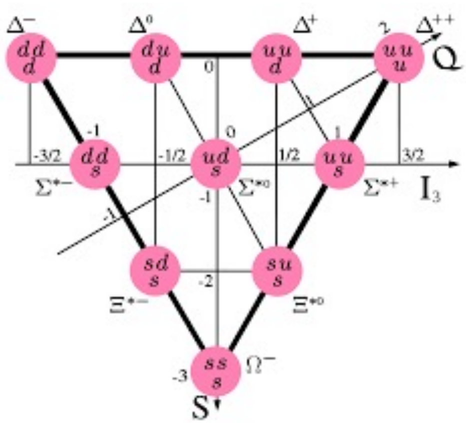
5 Descriptions consistent with experimental data at high Q^2.

Electromagnetic (time like and space like) baryon transition form factors



Phys.Rev.*C* 77 015202 (2008) ; Phys.Rev.*C* 77 035203 (2008) (Nucleon)
PhysRevD.85.093005 (2012); PhysRevD.85.093006 (2012); (Nucleon and DIS)

Phys.Rev.D 78 114017 (2008) (N-> Delta(1232) D waves)
Eur. Phys. J. A 36, 329–348 (2008) (N and Delta(1232))
J. Phys. G: Nucl. Part. Phys. 36 115011 (2009) (N-> Delta)
Phys.Rev.*D* 80 013008 (2009) (N-> Delta(1232) LQC link)
Phys.Lett.B 678 355-358 (2009) Delta(1232) D waves
Phys.Rev.D 81 113011 (2010) Delta(1232) D waves



PhysRevD.84.033007 (2011) (N->N*(1535))
Phys.Rev.D 83 054011 (2011) Omega
Phys.Rev.D 89 9, 094016 (2014) (N->N*(1520))

Phys.Rev.D 85 113014 (2012) (Delta(1232) Time like)
Phys.Rev.D 93 3, 033004 (2016) (Delta(1232) Time like)
Phys.Rev.D 95 1, 014003 (2017) (N*(1520) Timelike)

Phys.Rev.D 101 (2020) 1, 014014, (2020) (Hyperons Time like)
Phys.Rev.D 101 (2020) 11, 114008, (2020) N*(1535) Dalitz decay

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